

## SPITZER QUASAR AND ULIRG EVOLUTION STUDY (QUEST). I. THE ORIGIN OF THE FAR-INFRARED CONTINUUM OF QSOs

M. SCHWEITZER, D. LUTZ, E. STURM, A. CONTURSI, L. J. TACCONI, M. D. LEHNERT, K. M. DASYRA, AND R. GENZEL  
 Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, 85741 Garching, Germany; schweitzer@mpe.mpg.de, lutz@mpe.mpg.de,  
 sturm@mpe.mpg.de, contursi@mpe.mpg.de, linda@mpe.mpg.de, mlehnert@mpe.mpg.de, dasyra@mpe.mpg.de, genzel@mpe.mpg.de

S. VEILLEUX, D. RUPKE, D.-C. KIM, AND A. J. BAKER<sup>1</sup>

Department of Astronomy, University of Maryland, College Park, MD 20742-2421; veilleux@astro.umd.edu, drupke@astro.umd.edu,  
 dckim@astro.umd.edu, ajb@astro.umd.edu

H. NETZER AND A. STERNBERG

School of Physics and Astronomy and the Wise Observatory, The Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv  
 University, Tel-Aviv 69978, Israel; netzer@wise1.tau.ac.il, amiel@wise.tau.ac.il

AND

J. MAZZARELLA AND S. LORD

IPAC, California Institute of Technology, MS 100-22, Pasadena, CA 91125; mazz@ipac.caltech.edu, lord@ipac.caltech.edu

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### ABSTRACT

This paper addresses the origin of the far-infrared (FIR) continuum of QSOs, based on the Quasar and ULIRG Evolution Study (QUEST) of nearby QSOs and ULIRGs using observations with the *Spitzer Space Telescope*. For 27 Palomar-Green QSOs at  $z \lesssim 0.3$ , we derive luminosities of diagnostic lines ([Ne II] 12.8  $\mu\text{m}$ , [Ne V] 14.3  $\mu\text{m}$ , [O IV] 25.9  $\mu\text{m}$ ) and emission features (PAH 7.7  $\mu\text{m}$  emission, which is related to star formation), as well as continuum luminosities over a range of mid- to far-infrared wavelengths between 6 and 60  $\mu\text{m}$ . We detect star-formation-related PAH emission in 11/26 QSOs and fine-structure line emission in all of them, often in multiple lines. The detection of PAHs in the average spectrum of sources that lack individual PAH detections provides further evidence for the widespread presence of PAHs in QSOs. Similar PAH/FIR and [Ne II]/FIR ratios are found in QSOs and in starburst-dominated ULIRGs and lower luminosity starbursts. We conclude that the typical QSO in our sample has at least 30% but likely most of the far-infrared luminosity ( $\sim 10^{10}$ – $10^{12} L_{\odot}$ ) arising from star formation, with a tendency for larger star formation contribution at the largest FIR luminosities. In the QSO sample, we find correlations between most of the quantities studied including combinations of AGN tracers and starburst tracers. The common scaling of AGN and starburst luminosities (and fluxes) is evidence for a starburst-AGN connection in luminous AGN. Strong correlations of far-infrared continuum and starburst related quantities (PAH, low-excitation [Ne II]) offer additional support for the starburst origin of far-infrared emission.

*Subject headings:* galaxies: active — galaxies: starburst — infrared: galaxies — quasars: emission lines

*Online material:* color figures

### 1. INTRODUCTION

The infrared properties of luminous active galactic nuclei (AGNs) and ultraluminous infrared galaxies (ULIRGs) hold clues for the understanding of galaxy formation, the star formation history of the universe and the connection between black hole and galaxy formation and evolution. Physical insight into the coevolution of AGNs and star formation can be gained by study of the low-redshift members of these populations. The *Infrared Astronomical Satellite* (IRAS) and the *Infrared Space Observatory* (ISO) have allowed the first comprehensive far-infrared (FIR) studies of extragalactic sources and some high-quality mid-infrared (MIR) observations on the brighter sources (see e.g., the review of Genzel & Cesarsky 2000). Issues discussed in IRAS and ISO studies include the nature of ultraluminous infrared galaxies and their starburst and AGN energy sources (Genzel et al. 1998; Klaas et al. 2001), and the spectral energy distributions (SEDs) of QSOs and their evolutionary implications (Haas et al. 2003). A 2.5–45  $\mu\text{m}$  spectral inventory of starburst and AGN prototypes (Sturm et al.

2000) and detailed MIR spectroscopic investigations of local lower luminosity AGNs (Clavel et al. 2000; Sturm et al. 2002, hereafter S02) have addressed AGN unification and the starburst-AGN connection.

The *Spitzer Space Telescope* (hereafter *Spitzer*) has enabled us to build on previous work with significantly improved sensitivity. This work is part of a series of papers describing the results of the Quasar and Ulirg Evolution Study (QUEST), focussing on MIR spectroscopy of a sample of 54 QSOs and ULIRGs at redshifts  $z \lesssim 0.3$  with the Infrared Spectrograph (IRS) on board *Spitzer*. The sample was selected with the aim of investigating the possible connections between those two groups of luminous ( $L_{\text{Bol}} \gtrsim 10^{12} L_{\odot}$ ) objects in the nearby universe, and is closely connected to optical and near-infrared studies of the morphology and dynamical properties of these two populations (e.g., Dasyra et al. 2006a, 2006b; Veilleux et al. 2006). The purpose of the present paper is to study starburst signatures in QSO host galaxies and to show that most, and in some cases all, of the FIR luminosity in QSOs showing strong polycyclic aromatic hydrocarbon (PAH) features is due to starburst activity. A forthcoming complementary paper addresses the SED of QSOs including the

<sup>1</sup> Jansky Fellow, National Radio Astronomy Observatory.

clear FIR starburst contribution to the  $\lambda > 30 \mu\text{m}$  continuum of QSOs.

To investigate the link between AGN activity and star formation and the extent to which they occur simultaneously, it is important to quantify the star formation activity in QSO hosts. Such measurements are made difficult, however, by the observational problems of detecting star formation tracers in the presence of extremely powerful AGN emission. SED studies based on the *IRAS* and *ISO* space missions have established QSOs as sources of (sometimes) strong FIR emission. (e.g., Neugebauer et al. 1986; Haas et al. 2003). In addition to a nonthermal continuum that is detectable in the infrared only in flat spectrum radio-loud QSOs (e.g., Haas et al. 1998), a strong FIR emission component is often observed, at varying levels with respect to the strong AGN MIR continuum. Due to its steep falloff in the submillimeter regime, the origin of this FIR emission must be thermal emission of optically thin dust (Chini et al. 1989; Hughes et al. 1993). While the warmer  $T \sim 200 \text{ K}$  dust, which dominates the MIR SEDs of QSOs, is generally accepted to be predominantly AGN heated, there is still considerable dispute about the origin of the cooler  $T \sim 50 \text{ K}$  emission often dominating the FIR. Direct heating by the powerful AGNs, but at distances ensuring sufficiently low temperatures, is one possibility (e.g., Sanders et al. 1989; Haas et al. 2003; Ho 2005). Other models prefer an origin in vigorous star formation in the QSO host (e.g., Rowan-Robinson 1995). Rowan-Robinson (1995) used radiative transfer modeling to infer an SED of AGN-heated dust that, in  $\nu L_\nu$  units, peaks in the MIR, and decays toward the FIR, a feature shared by many other such models. In the QSO SEDs that are often flat over a wide wavelength range including the FIR, the FIR component is then plausibly ascribed to a component with an SED similar to that of a star-forming galaxy, in accordance with evidence for coexistence of star formation and AGNs in spatially resolved lower luminosity AGNs. Rowan-Robinson (1995) found a tight correlation of AGN optical emission and MIR continuum and a weaker correlation between optical and FIR emission, which is supporting the view that the FIR does not result directly from AGN heating but that there is a connection between AGNs and starburst luminosities in the QSOs.

Our goals are to quantify star formation in QSO hosts and to estimate its contribution to the FIR emission. In the MIR, the contrast between the emission from possibly dust-obscured star formation and from the central AGN is favorable, and established star formation tracers are available. We use two such tracers:

1. The MIR broad aromatic “PAH” emission features arise in regions of the interstellar medium of a galaxy where their aromatic carriers are present, and where their transient excitation is made possible by a non-ionizing ( $< 13.6 \text{ eV}$ ) soft UV radiation field. This is the case in the photodissociation regions (PDRs) that accompany Galactic star formation regions (e.g., Verstraete et al. 1996), as well as in the diffuse interstellar medium where they are excited by the general interstellar UV radiation field that has leaked from its OB star origins to large scales (e.g., Mattila et al. 1996). PAHs have been used as a quantitative tracer of star formation in galaxies (e.g., Genzel et al. 1998; Förster Schreiber et al. 2004; Calzetti et al. 2005). Metallicity above 0.2 solar is a prerequisite for strong PAH emission (Engelbracht et al. 2005), a condition that is probably safely met for local QSO hosts. Destruction of the PAH carriers in energetic environments but survival in starburst PDRs (although not in H II regions proper) is key for the use of PAH features as diagnostic. The PAH features are absent from the hard radiation environment of AGNs according to both empirical (e.g., Roche et al. 1991; Le Floc’h

et al. 2001; Siebenmorgen et al. 2004b) and theoretical (Voit 1992) studies. The latter suggest that PAH molecules hit by single energetic EUV/X-ray photons can be efficiently destroyed by photo-thermo dissociation or Coulomb explosion. Since AGNs are copious emitters of hard photons, PAH molecules near AGNs will be destroyed unless shielded by a large obscuring column.

2. The low-excitation fine-structure emission lines such as [Ne II]  $12.8 \mu\text{m}$  are among the dominant emission lines of H II regions. Observations of starburst galaxies, as well as a combination of evolutionary synthesis and photoionization modeling, show [Ne II]  $12.8 \mu\text{m}$  to be stronger than higher excitation MIR lines ([Ne V], [O IV], and [Ne III]) in typical ionized regions excited by young stellar populations (Thornley et al. 2000; Verma et al. 2003). Use of low-excitation lines as star formation tracers requires, however, the consideration of possible contributions from the AGN narrow-line region (NLR), which can be significant despite the generally higher excitation of such regions (e.g., Spinoglio & Malkan 1992; Alexander et al. 1999) compared to starburst H II regions.

Section 2 of the paper describes the sample, observations and data reduction used to obtain the line and continuum fluxes in our sources. Emission lines that are relevant to the present study are tabulated for all sources. In § 3 we discuss the widespread presence of PAH emission and its relation to other components of the QSO spectra. Finally, § 4 addresses the issue of star formation in host galaxies of QSOs, shows the importance of this process, and compares our results with earlier findings. In a forthcoming paper, we discuss the implications of our results for QSO SEDs in general. We adopt  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ , and  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

## 2. THE QUEST PG QSO SAMPLE: OBSERVATIONS AND REDUCTION

### 2.1. The Sample

As part of the *Spitzer* spectroscopy project QUEST (PID 3187; PI Veilleux) we are studying QSOs, ultraluminous infrared galaxies, and the possible evolutionary connection between the two using the IRS (Houck et al. 2004). The QSO sample is largely drawn from that of Guyon (2002) and Guyon et al. (2006). It consists of Palomar-Green (PG) QSOs (Schmidt & Green 1983) and covers the full ranges of bolometric luminosity ( $\sim 10^{11.5} - 10^{13} L_\odot$  based on the *B*-band absolute magnitude and the SED of Elvis et al. 1994), radio loudness, and infrared excess [ $\log(\nu L_\nu(60 \mu\text{m})/L_{\text{Bol}}) \sim 0.02 - 0.35$ ] spanned by the local members of the PG QSO sample (see also Jester et al. 2005, for a recent view on selection effects in the PG sample). B2 2201+31A is not a PG QSO but is in the sample because its *B* magnitude actually satisfies the PG QSO completeness criterion of Schmidt & Green (1983). It is one of the five radio-loud systems in our sample. At the sample’s maximum redshift of 0.325, important emission lines such as [O IV]  $25.89 \mu\text{m}$  stay within the IRS spectral range for all objects. The QUEST sample used in this paper includes 23 of 32 objects from the Guyon sample. We exclude here two recently observed QUEST objects that are not yet fully processed by the *Spitzer* pipeline. We add two Palomar-Green objects from the Guyon et al. sample previously observed by *Spitzer* (PG 0050 + 124 = IZw 1 [Weedman et al. 2005] and PG 0157 + 001 = Mrk 1014 [Armus et al. 2004]) and two PG QSOs from another project (PID 20241; PI Lutz). Table 1 lists names and redshifts of all 27 QSOs in our sample. In total, our sample covers a range from  $M_B = -21$  to

TABLE 1  
QSO SAMPLE

Object (1)	$z$ (2)	$S_6$ (mJy) (3)	$S_{15}$ (mJy) (4)	$S_{30}$ (mJy) (5)	$S_{60}$ (mJy) (6)	$S_{100}$ (mJy) (7)	Reference (8)	$D_L$ (Mpc) (9)	$\log(\nu L_\nu(60 \mu\text{m}))$ ( $L_\odot$ ) (10)
PG 0026+129.....	0.1420	16.2	35.8	74	<162	<129	1	672	<11.10
PG 0050+124 (IZw1).....	0.0611	178.3	515.1	1183	2243	2634	2	274	11.45
PG 0157+001 (Mrk 1014).....	0.1630	32.1	217.3	1352	2224	2164	2	781	12.39
PG 0838+770.....	0.1310	12.1	46.3	105	167	180	3, 4	615	11.06
PG 0953+414.....	0.2341	21.3	33.0	34	<129	<315	3	1170	<11.71
PG 1001+054.....	0.1605	16.8	34.5	69	140	146	4	768	11.18
PG 1004+130.....	0.2400	17.2	74.8	164	191	<284	5	1203	11.74
PG 1116+215.....	0.1765	54.5	78.4	113	<219	<285	4	853	<11.50
PG 1126-041 (Mrk 1298).....	0.0600	37.2	101.9	311	669	1172	3	269	10.93
PG 1229+204 (Mrk 771).....	0.0630	28.2	88.3	183	241	317	4	283	10.52
PG 1244+026.....	0.0482	15.8	66.7	194	368	362	4	214	10.44
PG 1302-102.....	0.2784	21.3	80.4	201	343	343	1, 5	1425	12.14
PG 1307+085.....	0.1550	...	50.2	101	212	155	4, 5	739	11.29
PG 1309+355.....	0.1840	22.1	70.9	106	<162	<192	4	893	<11.40
PG 1411+442.....	0.0896	61.4	96.9	139	147	140	1	410	10.62
PG 1426+015.....	0.0865	55.1	135.3	251	350	312	4	395	10.96
PG 1435-067.....	0.1260	18.3	33.3	77	304	<333	4	590	11.28
PG 1440+356 (Mrk 478).....	0.0791	55.1	135.3	251	597	780	4	359	11.13
PG 1448+273.....	0.0650	19.0	70.1	117	117	<252	5	292	10.22
PG 1613+658 (Mrk 876).....	0.1290	55.7	120.2	298	591	1002	1	605	11.64
PG 1617+175.....	0.1124	24.4	41.0	56	<98	<252	5	522	<10.77
PG 1626+554.....	0.1330	11.7	14.0	3	<156	70	4	626	10.66
PG 1700+518.....	0.2920	51.4	127.8	...	348	374	4	1505	12.22
PG 2214+139 (Mrk 304).....	0.0658	56.0	76.8	80	337	<282	3	296	10.68
B2 2201+31A.....	0.2950	32.2	58.4	...	<295	<870	6	1553	<12.43
PG 2251+113.....	0.3255	15.4	35.6	...	<67	<214	3	1706	<11.92
PG 2349-014.....	0.1740	21.2	59.8	167	271	290	5	840	11.55

NOTES.— Col. (1): Source name. Col. (2): Redshift. Cols. (3)–(5): Observed narrowband continuum flux densities around 6, 15, and 30  $\mu\text{m}$  rest wavelength, extracted from the *IRS* spectra. Missing entries are outside the rest wavelength range available for a given object. Cols. (6)–(8): *ISO* or *IRAS* fluxes at observed 60 and 100  $\mu\text{m}$ , and related references. Col. (9): Luminosity distance in Mpc for a  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$  cosmology. Col. (10): FIR luminosity. See text for treatment of limits.

REFERENCES.— (1) Haas et al. 2000; (2) *IRAS* Faint Source Catalog; (3) Neugebauer et al. 1986; (4) Haas et al. 2003; (5) Sanders et al. 1989; (6) from *IRAS* Addscan/Scanpi,

$M_B = -26$ , with median  $-23.3$ . In the remainder of this paper, we compare some aspects of the PG QSOs to ultraluminous infrared galaxies whose properties will be presented in more detail in an upcoming paper based on QUEST data (S. Veilleux et al. 2006, in preparation).

## 2.2. Data Reduction and Line and Continuum Measurements

For the QUEST sample, spectra were taken both at 5–14  $\mu\text{m}$  in the low-resolution (SL [short-low]) mode and at 10–37  $\mu\text{m}$  in the high-resolution (SH [short-high] and LH [long-high]) modes of the *IRS*. Slit widths of  $3''.6$  to  $11''.1$  include much of the QSO hosts, as well as the vicinity of the AGNs. Our data reduction starts with the two-dimensional basic calibrated data (BCD) products provided by version 12 of the *Spitzer* pipeline reduction. We used our own IDL-based tools for removing outlying values for individual pixels and for sky subtraction, and SMART (Higdon et al. 2004) for extraction of the final spectra. Small multiplicative corrections were applied to stitch together the individual orders of the low-resolution and high-resolution spectra, as well as additive corrections for residual offsets still found between the low-resolution spectra and the SH and LH high-resolution spectra after zodiacal light correction of the latter. Emission-line fluxes were measured using fits of Gaussian lines superposed on a local continuum. PAH fluxes were mostly measured by simultaneously fitting Lorentzians to the main 6.2, 7.7, and 8.6  $\mu\text{m}$  features superposed on a 5.3–9.6  $\mu\text{m}$  (rest-frame) continuum approximated by a second-order polynomial, and in a few cases by combined

Lorentzian and continuum fits over smaller ranges. We use below the flux for the brightest (7.7  $\mu\text{m}$ ) feature as PAH strength indicator  $F_{\text{PAH}}$ . In PG 0050+124, where this feature was present but difficult to quantify in the presence of strong silicate emission, we have estimated the flux scaling from the flux of the well-detected 6.2  $\mu\text{m}$  PAH feature, using the 7.7/6.2 feature ratio measured in the starburst/AGN NGC 6240 (Lutz et al. 2003; Armus et al. 2006). Flux upper limits ( $3 \sigma$ ) were derived adopting typical widths for the lines ( $\sim 600 \text{ km s}^{-1}$ ) and broad features ( $\sim 0.6 \mu\text{m}$  for the 7.7  $\mu\text{m}$  feature). In one source (PG 1307+085) we could only analyze the high-resolution spectra since low-resolution data are proprietary to another program. This limits our sample to 26 objects for analysis related to PAH emission. QUEST data for ultraluminous infrared galaxies that are used for comparison with the QSOs were processed in the same way.

Figure 1 shows individual example spectra of two PG QSOs illustrating the broad differences between QSOs with strong and weak PAH emission. Table 1 also lists the continuum flux densities in several MIR and FIR bands. In the MIR, the quality of the *IRS* spectra is superior to most preexisting *IRAS* or *ISO* photometry. For that reason and to characterize the continuum at wavelengths reasonably free of emission features, we have derived average observed flux densities over narrow bands ( $\Delta\lambda/\lambda \sim 0.07$ ) centered at several rest wavelengths. The shortest wavelength continuum point at 6  $\mu\text{m}$  is shortward of the main PAH complex; the 15  $\mu\text{m}$  point is between the two silicate emission

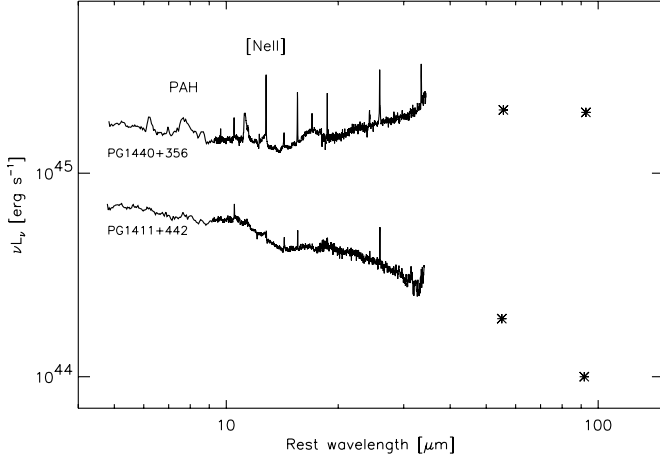


FIG. 1.— IRS spectra of two PG QSOs, combined with FIR photometric fluxes. These two nearby sources were selected to illustrate the full range between sources with strong PAH, [Ne II], and FIR emission and others with weak emission in all these tracers. The spectrum of PG 1440+356 has been multiplied by a factor of 4 for clarity.

peaks at about 10 and 18  $\mu\text{m}$  (Siebenmorgen et al. 2005; Hao et al. 2005; Sturm et al. 2005), but still partly affected by silicate emission if present. The longest wavelength point at 30  $\mu\text{m}$  is near the long end of the *IRS* spectra and already beyond the strongest part of the longer wavelength silicate feature. We later use continuum luminosities at these rest wavelengths: 6, 15, and 30  $\mu\text{m}$ , defined as  $\nu L_\nu$ .

FIR fluxes have been taken from the literature, usually giving preference to *ISO*-based results over *IRAS*-based ones, because the smaller effective *ISO* beams reduced the susceptibility to cirrus

contamination at 100  $\mu\text{m}$ . The FIR luminosity,  $L(\text{FIR})$ , is often obtained from  $F_{\text{FIR}}$ , which is defined as  $F_{\text{FIR}} = 1.26(S_{100} + 2.58 \times S_{60}) \times 10^{-18} \text{ W cm}^{-2}$ , where  $S_{100}$  and  $S_{60}$  are flux densities in Jy (e.g., Sanders & Mirabel 1996). In order to use a consistent definition over the full  $z \leq 0.33$  redshift range of our sample and to reduce the sensitivity to galactic cirrus contamination that is most problematic at 100  $\mu\text{m}$ , we adopt a FIR luminosity,  $\nu L_\nu$ , that is solely based on the flux at rest wavelength 60  $\mu\text{m}$  interpolated from the photometry in the literature. Even nearby QSOs are typically close to the FIR detection limits of the previous space missions. In six cases where only one of  $S_{100}$  or  $S_{60}$  was detected we estimated the other flux as the lower of the measured limit and an extrapolation using the detected flux and the ratio  $S_{60}/S_{100} = 0.93$  that is the median for the part of the sample detected in both bands. The flux at 60  $\mu\text{m}$  rest wavelength was interpolated linearly between the observed 60 and 100  $\mu\text{m}$  points. For seven PG QSOs in our sample that are undetected in both bands, upper limits on  $\nu L_\nu$  at 60  $\mu\text{m}$  rest wavelength were derived in an analogous way interpolating linearly between the limits at observed wavelengths of 60 and 100  $\mu\text{m}$ . Since QSO fluxes are close to the detection limits of the original *IRAS* and *ISO* references and because of residual cirrus contamination, uncertainties of order 30%–50% for the FIR fluxes may well occur.

### 3. RESULTS

Table 2 lists the intensities of the three emission lines used in the present analysis, [Ne II] 12.8  $\mu\text{m}$ , [Ne V] 14.3  $\mu\text{m}$ , [O IV] 25.9  $\mu\text{m}$ , and of the emission feature PAH 7.7  $\mu\text{m}$ . The table includes detections as well as upper limits. A more comprehensive list including more lines will be given in a forthcoming paper.

TABLE 2  
MEASURED EMISSION FEATURES

Object	[Ne II] 12.8 $\mu\text{m}$ ( $\text{W cm}^{-2}$ )	[Ne V] 14.3 $\mu\text{m}$ ( $\text{W cm}^{-2}$ )	[O IV] 25.9 $\mu\text{m}$ ( $\text{W cm}^{-2}$ )	PAH 7.7 $\mu\text{m}$ ( $\text{W cm}^{-2}$ )
PG 0026+129.....	2.29E-22	4.73E-22	2.14E-21	<8.70E-21
PG 0050+124.....	1.94E-21	5.50E-21	7.25E-21	7.29E-20
PG 0157+001.....	5.52E-21	5.18E-21	1.17E-20	5.93E-20
PG 0838+770.....	4.11E-22	3.24E-22	1.30E-21	1.04E-20
PG 0953+414.....	<1.70E-22	<1.90E-22	5.08E-22	<2.33E-20
PG 1001+054.....	4.00E-22	<1.20E-22	5.19E-22	<1.32E-20
PG 1004+130.....	<2.43E-22	<2.76E-22	2.10E-21	<1.47E-20
PG 1116+215.....	<3.20E-22	<2.90E-22	1.10E-21	<3.50E-20
PG 1126-041.....	1.39E-21	4.34E-21	1.59E-20	1.49E-20
PG 1229+204.....	6.13E-22	9.06E-22	2.77E-21	<1.40E-20
PG 1244+026.....	9.42E-22	5.31E-22	1.51E-21	6.02E-21
PG 1302-102.....	3.56E-22	4.87E-22	2.60E-21	<8.52E-21
PG 1307+085.....	3.98E-22	5.63E-22	7.38E-22	...
PG 1309+355.....	5.07E-22	2.69E-22	<4.95E-22	<3.80E-20
PG 1411+442.....	3.61E-22	9.56E-22	1.49E-21	1.02E-20
PG 1426+015.....	1.29E-21	1.25E-21	3.43E-21	2.36E-20
PG 1435-067.....	<1.05E-22	5.22E-22	3.88E-22	<5.20E-21
PG 1440+356.....	4.11E-21	1.33E-21	6.26E-21	7.38E-20
PG 1448+273.....	5.07E-22	2.67E-21	1.01E-20	1.55E-20
PG 1613+658.....	3.88E-21	1.13E-21	4.89E-21	3.86E-20
PG 1617+175.....	2.89E-22	<1.70E-22	3.92E-22	<1.05E-20
PG 1626+554.....	6.91E-23	<6.90E-23	<1.97E-22	<7.10E-21
PG 1700+518.....	1.21E-21	<2.30E-22	1.68E-21	<2.40E-20
PG 2214+139.....	2.26E-22	2.70E-22	1.27E-21	<1.30E-20
B2 2201+31A.....	9.64E-23	5.31E-22	5.62E-22	<7.89E-21
PG 2251+113.....	1.69E-22	4.90E-22	3.08E-21	<8.00E-21
PG 2349-014.....	1.44E-21	7.05E-22	3.87E-21	1.66E-20

### 3.1. PAH Emission is Common in QSOs

As is clear from inspection of Table 2, some of the QSOs in our sample show only high-excitation lines, likely originating in the NLRs of these objects. Others (11 of 26) show prominent PAH 7.7  $\mu\text{m}$  and other PAH features, indicative of significant star formation. The existence of “composite” sources (see S02 for definition and references to *ISO*-based studies) that show both AGN and starburst properties, has been known for several years. Such sources contain both powerful star-forming regions, giving rise to the observed PAH emission through near-UV heating, and high-luminosity NLRs that are excited by the central radiation source. Since the star-forming activity is a property of the host galaxy, and the NLR line luminosities scale with the AGN continuum luminosity, the intensity of the starburst emission features relative to the continuum might be expected to be weaker in AGNs whose luminosities are in the QSO regime. Because the S02 sample included only three objects with QSO-like luminosities [i.e.,  $L(\text{FIR}) > 5 \times 10^{11} L_{\odot}$ ] and suffered from the limited S/N achievable with *ISO*, a quantitative verification of this idea was not possible up to now.

Our new sample includes 27 high-luminosity AGNs, and it is therefore important that the fraction of clear PAH emitters in the sample is large. This is strengthened further by the detection of PAH 7.7 and 11.3  $\mu\text{m}$  peaks in the average spectrum of the 15 QSOs not showing *individual* PAH detections (Fig. 2, *bottom*). Since this average spectrum excludes sources with individual PAH detections, the PAH emission seen is unlikely to be due to a few PAH-strong sources only, in an otherwise largely PAH-free group. It also has the implication that typically the true PAH fluxes of the PAH nondetections cannot be far below our limits. This high incidence of PAH emission is our first major conclusion and is further discussed in the following sections.

### 3.2. Trends with Level of PAH Emission

Before embarking on an analysis of the correlations of different starburst and AGN tracers, we use the two average spectra of the PG QSOs that are individually detected in PAH emission (11 objects) or individually undetected in PAH emission (15 objects) (Fig. 2) to identify some of the salient trends in our data. The two spectra have been obtained by averaging the individual spectra after normalizing to the same total flux in the MIR 5–25  $\mu\text{m}$  rest wavelength region. We caution that significant variations are present also within those two groups.

1. PAH 7.7  $\mu\text{m}$  is 2.5 times stronger (relative to the total 5–25  $\mu\text{m}$  MIR flux) in the average of the objects with individual PAH detections. This is a natural consequence of the object grouping for the two average spectra. As noted, the relatively small difference argues for the presence of PAH emission in most of the objects that did not have individual detections.

2. The FIR continuum emission is relatively stronger than the MIR continuum in the objects with PAH detections. This is apparent in several ways. First, all PAH detections are also FIR (60  $\mu\text{m}$  rest-frame) detections while 7 of 15 PAH nondetections are also not detected in the FIR. Second, the mean ratio  $\nu F_{\nu}(60 \mu\text{m})/\nu F_{\nu}(6 \mu\text{m})$  is  $1.72 \pm 0.54$  for the 11 PAH detections,  $1.00 \pm 0.15$  for the eight FIR-detected PAH nondetections,  $<0.88$  for the seven objects undetected in both FIR and PAH, and finally  $<0.94$  for all eight + seven PAH nondetections. The values for the two upper limits assume that the FIR fluxes are less than or equal to the measured limits for the individual FIR nondetections. Third, inspection of the average IRS spectra in Figure 2 shows significant differences in the extrapolation to 60  $\mu\text{m}$ . The average

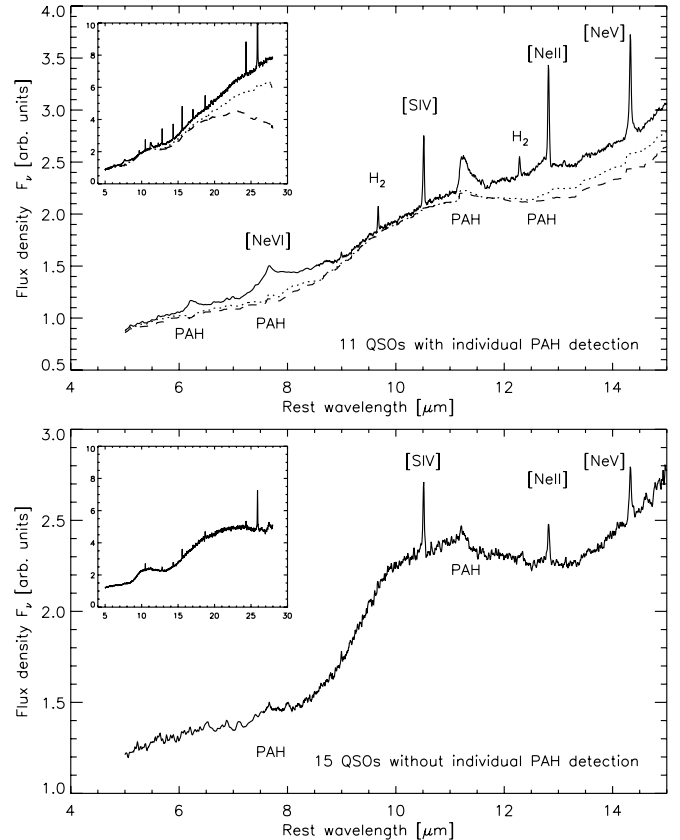


Fig. 2.—Average spectra of QSOs. Individual spectra have been normalized to the same total 5–25  $\mu\text{m}$  flux before averaging. Note the change in spectral resolution from low at short wavelengths to high at  $\geq 9 \mu\text{m}$  rest wavelength. *Top*: 11 QSOs for which PAH 7.7  $\mu\text{m}$  is detected in the individual spectra. The dotted line is the same spectrum after subtracting an M82 spectrum scaled to the PAH features, and the dashed line after subtracting a starburst-dominated ULIRG spectrum scaled to the PAH features. Emission-line residuals have been removed for clarity. The inset repeats the same spectra with different plot scaling, emphasizing the wider range SED trends. *Bottom*: 15 QSOs for which PAH 7.7  $\mu\text{m}$  is not detected individually. A broad maximum near 7.7  $\mu\text{m}$  rest wavelength as well as an 11.3  $\mu\text{m}$  feature is detected in the average, however, indicating a high incidence of PAH emission in the contributing spectra.

spectrum of the PAH detections continues to rise beyond 25  $\mu\text{m}$ , while there is an indication for a downturn in the average of the PAH nondetections beyond this wavelength. Regardless of uncertainties in the extrapolation that are related to the assumed intrinsic spectral shape and to technical issues such as IRS spectral response calibration and zodiacal light subtraction, the 60/6  $\mu\text{m}$  flux density ratio must be significantly larger in the average spectrum of the sources with detected PAHs. We estimate that this ratio is larger for the PAH detections by a factor of 2 to 3.

We have also tentatively grouped the PAH nondetections into two average spectra for the eight FIR-detected and seven FIR-nondetected sources. While the statistics and signal-to-noise ratios (S/Ns) are poorer in these samples, there are indications that the sources undetected in both tracers are at the end of the physical trends described in items 1 and 2—little PAH, weak FIR, and indication for more of a downturn at  $\lambda > 25 \mu\text{m}$ ; that is, they are not just fainter overall.

3. The lower excitation [Ne II] line is stronger in the QSOs detected in PAHs. Normalized by the higher excitation lines [S IV] and [O IV], the [Ne II] line is 1.9 and 1.7 times stronger in the QSOs detected in PAHs compared to those undetected in PAHs.

4. The broad 10  $\mu\text{m}$  silicate emission peak is apparently weaker in the sources with detected PAHs. We argue this is largely an

artifact of having a stronger starburst component with its PAH emission. This is illustrated by the dotted line in the top panel of Figure 2, which shows the average spectrum after subtracting a PAH-dominated M82 spectrum (Sturm et al. 2000) roughly scaled to the PAH features, and the dashed line, which shows the equivalent result using the average of 12 starburst-dominated QUEST ULIRGs (see § 4.1) as a starburst template. As noted by, e.g., Sturm et al. (2000), a main difference between different starburst templates is in the level of increase of the  $\lambda \gtrsim 12 \mu\text{m}$  very small grain continuum, even for similar shorter wavelength PAH spectra. Our two choices illustrate the effect of such a template variation. The two PAH complexes around 7 and  $12 \mu\text{m}$  and the FIR upturn serve to “fill in” the minima between and around the two silicate emission peaks. This is analogous to the well-known difficulty of quantifying silicate *absorption* in spectra with strong PAH emission. We note that subtracting a starburst spectrum from the PAH-strong average QSO spectrum, in addition to recovering the correct pronounced silicate emission, also indicates a flatter or decreasing extrapolation to beyond  $25 \mu\text{m}$ , similar to what is seen in the PAH-weak average QSO spectrum.

5. Molecular hydrogen emission in the  $S(1)$ ,  $S(2)$ , and  $S(3)$  rotational lines has a larger equivalent width in the PAH-strong average spectrum, by factors of 3–5 comparing these detections with the detections/limits for the PAH-weak average spectrum.

All these trends are consistent with a starburst component (containing strong PAH and FIR continuum, low-excitation fine-structure line, and possibly molecular hydrogen emission) being superimposed in increasing proportion on a pure AGN spectrum (consisting of warm and hot dust continuum, silicate, and high-excitation line emission).

#### 4. DISCUSSION

##### 4.1. Nature of the QSO Far-Infrared Emission and the Starburst-AGN Connection

We use our sample to compare several AGN- and starburst related quantities observed in the PG QSOs, in an attempt to identify the likely origin of the FIR emission. We compare the starburst tracers in these QSOs with those of pure starbursts from two samples: (1) A subset of starburst-dominated QUEST ULIRGs observed with IRS (“SB-ULIRGs”). In order to restrict ourselves to the ULIRGs with the highest starburst contribution to their infrared luminosity, we require these objects to have no  $[\text{O IV}] 25.9 \mu\text{m}$  detection, a peak ratio of the PAH  $7.7 \mu\text{m}$  feature to its local continuum of at least 1, and a  $5\text{--}10 \mu\text{m}$  spectrum in which visual inspection shows that the absorption features like the  $6 \mu\text{m}$  ice feature are not dominant, although sometimes present. The last criterion is used to avoid ambiguities concerning the internal energy sources of the most heavily obscured ULIRGs (Spoon et al. 2004a, 2004b). (2) A small sample of six *ISO*-observed local starbursts (M82, NGC 253, NGC 1808, IC 342, NGC 3256, and NGC 7552) for which the PAH emission is measured without significant aperture corrections relative to the FIR data from *IRAS*, *ISO*, or the Kuiper Airborne Observatory (KAO). The ratio of PAH and FIR emission is known to vary somewhat with physical conditions (see e.g., discussion in § 4.2 of Lutz et al. 2003), decreasing with the average intensity of the radiation field (e.g., Dale et al. 2001). Because of these trends with ISM (interstellar medium) conditions, we add as another group of comparison objects (3) 12 “FIR-quiet” galaxies (with particularly low  $L_{\text{FIR}}/L_B$  and low  $S_{60}/S_{100}$ ) from the sample of normal galaxies of Lu et al. (2003), for which we convert their PAH fluxes measured in ISOPHOT-S spectra to our measurement procedure and apply aperture corrections

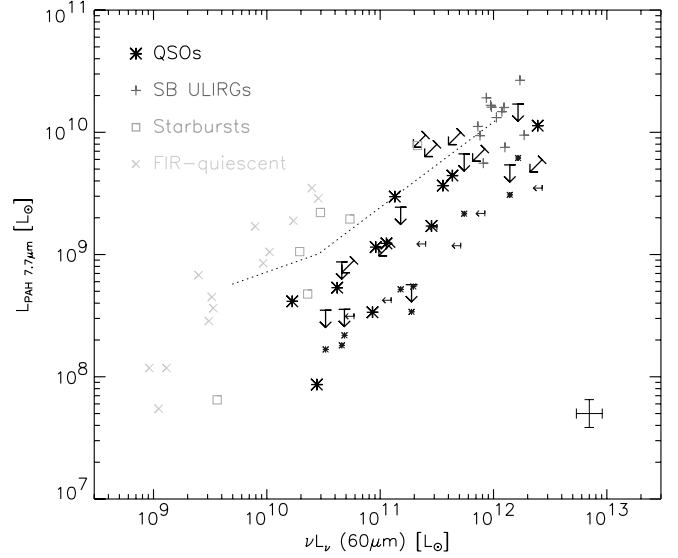


FIG. 3.—Luminosities  $L(\text{PAH } 7.7 \mu\text{m})$  vs.  $L(60 \mu\text{m})$  for the QSOs. Starburst-dominated ULIRGs, lower luminosity starbursts, and FIR-quiet galaxies are added for comparison. The thin dotted line connects the mean locations of these three groups of comparison objects. The small blue symbols repeat the QSOs without individual PAH detections, but assuming that the individual ratios of PAH  $7.7 \mu\text{m}$  to rest-frame  $5\text{--}25 \mu\text{m}$  flux are the same as in the average spectrum of Fig. 2 (bottom). A 30%  $1 \sigma$  uncertainty is indicated in the bottom right corner. [See the electronic edition of the Journal for a color version of this figure.]

based on their PAH-dominated ISOCAM LW2 images. We add to this group NGC 891 that has been mapped with ISOPHOT-S by Mattila et al. (1999), arriving at a sample of 13 FIR-quiet objects. The three comparison samples cover a range in luminosity, as well as in the average intensity of their interstellar radiation fields that is reflected in their MIR to FIR SEDs.

An important new result is the clear correlation between  $L(\text{PAH } 7.7 \mu\text{m})$  and  $L(\text{FIR})$  for the PAH-containing QSOs. Figures 3 and 4 compare the luminosities and fluxes of PAH  $7.7$  and  $60 \mu\text{m}$  continuum. The QSOs with PAH detections and the starburst-dominated ULIRGs follow the same trend. Figure 5 shows the equivalent continuous trend from QSOs to starburst-dominated ULIRGs for the comparison of  $[\text{Ne II}] 12.8$  and  $60 \mu\text{m}$  continuum.

These trends also imply almost identical mean ratios for the QSO and starburst-dominated ULIRG populations. For the 11 QSOs with both PAH and FIR emission detected we find  $\langle L(\text{PAH})/L(\text{FIR}) \rangle = 0.0110 \pm 0.0021$ , while for the 12 starburst-dominated ULIRGs we get  $\langle L(\text{PAH})/L(\text{FIR}) \rangle = 0.0130 \pm 0.0015$ . Similarly, comparing  $[\text{Ne II}] 12.8 \mu\text{m}$  and FIR emission we get for the 18 QSOs with both quantities detected  $\langle L([\text{Ne II}])/L(\text{FIR}) \rangle = (5.15 \pm 0.73) \times 10^{-4}$  and for the 12 starburst-dominated ULIRGs  $\langle L([\text{Ne II}])/L(\text{FIR}) \rangle = (4.22 \pm 0.57) \times 10^{-4}$ . In both cases, the ratio of the star formation indicator and FIR emission is the same in QSOs and in starburst-dominated ULIRGs—the observations are consistent with starbursts producing all of the QSO FIR emission if their specific properties are similar to those in starburst-dominated ULIRGs.

This argument depends on the adopted specific properties of the comparison star-forming galaxies, because of the changes of the PAH to  $60 \mu\text{m}$  ratio with ISM properties mentioned above. For ULIRG starbursts we obtained  $\langle L(\text{PAH})/L(\text{FIR}) \rangle = 0.0130 \pm 0.0015$ . For the six lower luminosity starbursts for which the ratio of PAH and FIR can be derived from *ISO* data without significant aperture corrections, we obtain  $\langle L(\text{PAH})/L(\text{FIR}) \rangle = 0.0399 \pm 0.0087$ . Finally, for the sample of 13 FIR-quiet

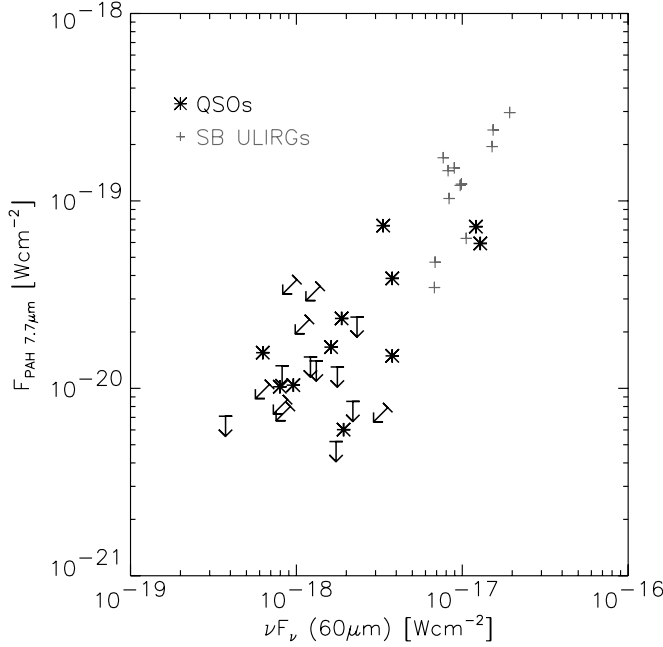


FIG. 4.—Fluxes  $F(\text{PAH } 7.7 \mu\text{m})$  vs.  $F(60 \mu\text{m})$  for the QSOs and for starburst-dominated ULIRGs. [See the electronic edition of the Journal for a color version of this figure.]

normal galaxies we get  $\langle L(\text{PAH})/L(\text{FIR}) \rangle = 0.126 \pm 0.016$  with individual objects like NGC 891 reaching up to a value 0.2.

Comparing these three ratios to the average of the QSOs, we find that almost all, at least  $\sim 30\%$ , and at least  $\sim 10\%$  of the QSO FIR emission would be due to non-AGN sources (that is current and recent star formation), adopting the values for ULIRGs, starbursts and FIR-quietest galaxies as templates. Irrespective of the adopted template, PAH-based values are lower limits since for QSOs there is the interesting possibility of additional weakening of PAH emission in star-forming regions that are also exposed to AGN radiation, by destruction of the PAH molecules. This may be particularly relevant if some of the FIR emission is generated by star formation occurring in compact clusters or disks very close to the AGNs (Davies et al. 2004a, 2004b). This makes values toward the upper end of the range for the non-AGN contribution more likely.

Using only PAH and FIR evidence, a formal solution is possible that maximizes the AGN fraction of the FIR emission by assigning the PAH emission to a very FIR-quietest galaxy. The QSO PAH luminosities are on average larger than those of the FIR quiescent galaxies, but the most luminous quiescent objects are of a similar PAH luminosity as the typical QSOs (Fig. 3). Comparing these objects to QSOs, the AGNs would then contribute roughly 90% of the QSO FIR flux. These objects yield biased comparisons, however, since they are specifically selected for FIR quietness. A fairer comparison would need to populate the PAH/FIR plane of Figure 3 with a large and complete sample of non-AGN galaxies. While such a sample is currently not available, we qualitatively indicate in Figure 3 the expected locus of such non-AGN galaxies by connecting the locations of the averages of our three small comparison samples (*dotted line*). While the FIR quiescent objects are likely more PAH luminous than the average galaxy of the same FIR luminosity, and thus their point placed too high, the overall trend of PAH flux with FIR flux is certainly robust, and the slope of this relation for non-AGN galaxies less than 1, in agreement with the photometric relation between total infrared and ISOCAM LW2 emission studied

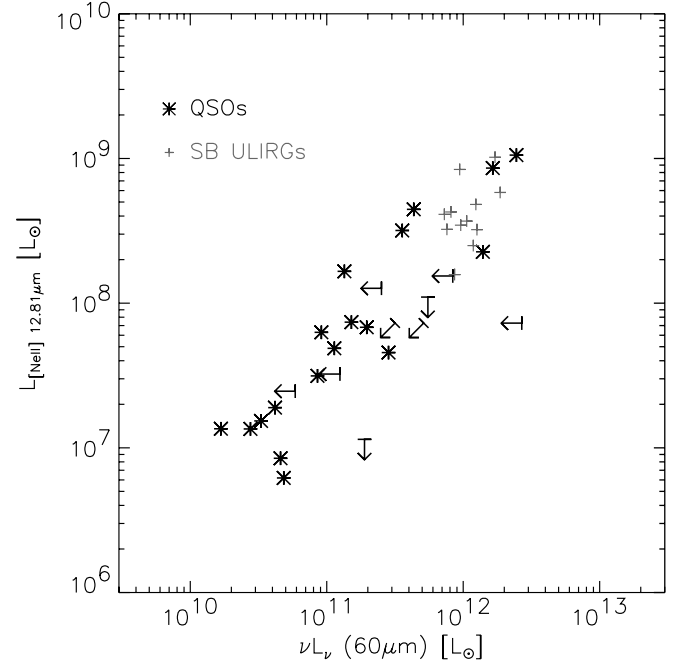


FIG. 5.—Luminosities  $L([\text{Ne II}] 12.8 \mu\text{m})$  vs.  $L(60 \mu\text{m})$  for the QSOs and for starburst-dominated ULIRGs. [See the electronic edition of the Journal for a color version of this figure.]

by Chary & Elbaz (2001). Applying such a luminosity-dependent ratio of PAH to FIR luminosity to QSOs is consistent with our finding of star formation dominating the FIR emission in many of our QSOs. The alternate scenario, in which host galaxies are all PAH luminous but FIR-quietest and the FIR emission of QSOs is AGN-dominated, is both complex and inconsistent with some of the evidence presented in § 3.2. Specifically, it cannot explain why both the FIR *and* the PAH emission rise together relative to the MIR continuum (i.e., AGNs) luminosity (see also Fig. 2). Moreover, this scenario does not agree with the multi-wavelength evidence for active star formation mentioned in § 4.3.

Considering these trends and the fact that the FIR luminosities of the PG QSOs are typically in the  $\geq 10^{11} L_{\odot}$  regime, we conclude that for the average QSO in the sample the star formation contribution to the FIR emission is at least 30% (applying the starburst PAH to 60  $\mu\text{m}$  conversion), and that star formation may well be dominant. Comparing the locus of QSOs in Figure 3 with the trend for star-forming comparison objects suggests a tendency for the star formation contribution to be largest in the most FIR-luminous QSOs.

Similar considerations can be made for the comparison of  $[\text{Ne II}] 12.8 \mu\text{m}$  and FIR emission in QSOs and ULIRGs (Fig. 5). Here the sources of uncertainty are the NLR contribution to  $[\text{Ne II}] 12.8 \mu\text{m}$  for the QSOs and the possibility of different extinction in the QSO starbursts and the ULIRGs, which show considerable MIR extinction (Genzel et al. 1998).

The similarity between QSOs and starburst-dominated ULIRGs in trends and ratios based on PAH 7.7  $\mu\text{m}$ ,  $[\text{Ne II}] 12.8 \mu\text{m}$ , and FIR continuum no longer holds when we plot a clearly AGN-related quantity on one axis. Figure 6 shows that the ratio of PAH and 6  $\mu\text{m}$  continuum differs between QSOs and starburst-dominated ULIRGs by more than an order of magnitude, and that the two classes separate clearly in the diagram. An additional strong nonstarburst component is required in the QSOs, which clearly is the AGN-heated warm dust continuum. We note, however, a clear correlation between the luminosities of AGN 6  $\mu\text{m}$  continuum and starburst PAH among the QSOs. We

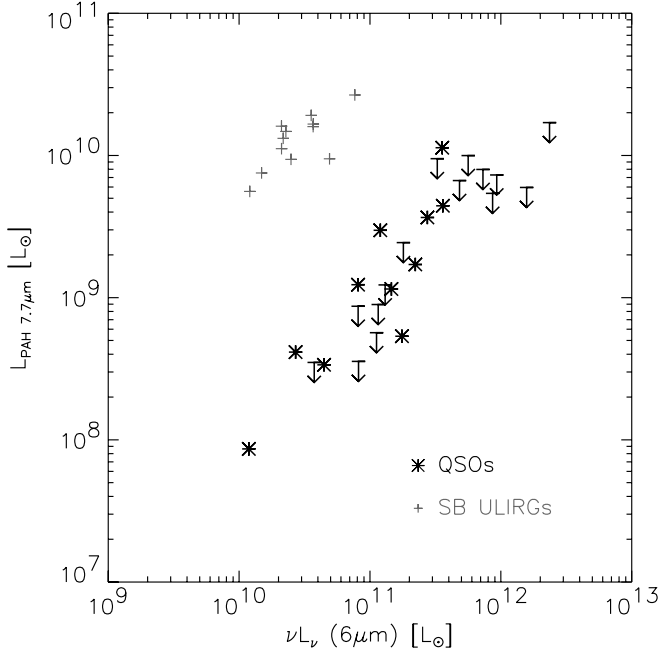


FIG. 6.—Luminosities  $L(\text{PAH } 7.7 \mu\text{m})$  vs.  $L(6 \mu\text{m})$  for the QSOs and for starburst-dominated ULIRGs. [See the electronic edition of the Journal for a color version of this figure.]

will now argue on the basis of a more comprehensive comparison that this correlation is indirect, caused by a starburst-AGN connection in QSOs.

In a flux-limited sample selected based on an emission component that is directly due to the AGNs, as is the case for the PG sample (selected by pointlike appearance,  $B$  magnitude, and blue  $U - B$  color), we expect correlations between the luminosities of the various AGN tracers to arise directly as a consequence of the sample selection. Correlations are not expected when comparing

AGN- and starburst-related quantities unless there is a real physical correlation.

A summary of correlation coefficients among the continua, PAH and line fluxes measured in the QSOs is given in Table 3. Some of the relations are also shown in Figures 3–8. In Table 3 we list Spearman rank correlation coefficients for the detected objects and their significance both for luminosities and for the observed fluxes. Given the selection of the PG sample over a relatively narrow flux range, the correlations in flux are generally less tight, but agree with the findings based on luminosities. Our data set includes upper limits, in particular for feature measurements and FIR fluxes, as well as trends between luminosity and distance caused by the flux limited selection. For these reasons, we also list in Table 3 partial correlation coefficients (explicitly excluding the effect of distance) that have been computed using the formalism of Akritas & Siebert (1996), which provides partial correlation analysis for censored data. The results from this analysis of the full censored data set are in agreement with those from the detections only.

A first and expected finding is the significant correlations between various luminosities tracing the AGN components, e.g.,  $6 \mu\text{m}$  continuum and the high-excitation emission lines. There is a noticeable spread in the ratio of MIR continuum emission and emission in the MIR high-excitation lines  $[\text{O IV}] 25.9 \mu\text{m}$  and  $[\text{Ne v}] 14.3 \mu\text{m}$ , however, equivalent to a spread in equivalent width of these lines. This is not uncommon in other AGN narrow emission lines such as  $[\text{O III}] \lambda 5007$  (e.g., Boroson & Green 1992; Baskin & Laor 2005) and has implications for the reliability of NLR lines as direct tracers of AGN bolometric luminosity. Netzer et al. (2006) discuss this large spread of  $[\text{O III}] \lambda 5007$  equivalent width, which is likely a general property of AGNs and also a function of source luminosity (the “Baldwin-effect”) and emission-line reddening.

Clear correlations are also seen between quantities tracing starburst activity (PAH  $7.7 \mu\text{m}$  being the cleanest) and others that in the QSOs must be almost fully dominated by the AGNs (like

TABLE 3  
CORRELATION OF MEASURED PROPERTIES

Property A (1)	Property B (2)	Number of Detections (3)	$R_S$ Luminosity (4)	Probability Luminosity (5)	$R_S$ Flux (6)	Probability Flux (7)	Dispersion (8)	Number All (9)	PKT (10)	Probability (11)
$60 \mu\text{m}$ .....	PAH	11	0.945	1.1E-5	0.582	6.0E-2	0.293	26	0.248	5.7E-3
$60 \mu\text{m}$ .....	$6 \mu\text{m}$	19	0.894	2.4E-7	0.567	1.1E-2	0.303	26	0.321	1.6E-2
$60 \mu\text{m}$ .....	$15 \mu\text{m}$	20	0.938	9.8E-10	0.746	1.6E-4	0.212	27	0.441	2.8E-4
$60 \mu\text{m}$ .....	$30 \mu\text{m}$	19	0.926	1.3E-8	0.825	1.4E-5	0.384	24	0.530	4.6E-5
$60 \mu\text{m}$ .....	$[\text{Ne II}]$	18	0.899	4.0E-7	0.744	4.0E-4	0.284	27	0.329	1.1E-3
$60 \mu\text{m}$ .....	$[\text{O IV}]$	19	0.670	1.7E-3	0.493	3.2E-2	0.422	27	0.267	1.4E-2
$60 \mu\text{m}$ .....	$[\text{Ne v}]$	16	0.788	2.9E-4	0.456	7.6E-2	0.345	27	0.257	3.1E-2
PAH.....	$6 \mu\text{m}$	11	0.873	4.6E-4	0.473	1.4E-1	0.283	26	0.174	6.2E-2
PAH.....	$15 \mu\text{m}$	11	0.927	1.0E-5	0.800	3.1E-3	0.219	26	0.277	5.3E-3
PAH.....	$30 \mu\text{m}$	11	0.927	4.0E-5	0.636	3.5E-2	0.268	23	0.346	1.6E-3
PAH.....	$[\text{Ne II}]$	11	0.936	2.2E-5	0.845	1.1E-3	0.246	26	0.287	1.1E-3
PAH.....	$[\text{O IV}]$	11	0.600	5.1E-2	0.436	1.8E-1	0.397	26	0.186	2.6E-2
PAH.....	$[\text{Ne v}]$	11	0.682	2.1E-2	0.636	3.5E-2	0.352	26	0.214	1.2E-2
$6 \mu\text{m}$ .....	$[\text{O IV}]$	24	0.657	4.8E-4	0.147	4.9E-1	0.482	26	0.264	8.4E-3
$6 \mu\text{m}$ .....	$[\text{Ne v}]$	19	0.770	1.2E-4	0.484	3.6E-2	0.366	26	0.256	4.0E-2

NOTES.—Col. (1): First variable. Wavelengths stand for continuum at that rest wavelength. Col. (2): Second variable. Col. (3): Number of sources detected in both quantities. Col. (4): Spearman’s rank correlation coefficient for luminosities, for detected sources. Col. (5): Probability of exceeding the measured correlation coefficient for luminosities in the null hypothesis of uncorrelated data. Smaller values indicate more significant correlations. Col. (6): Spearman’s rank correlation coefficient for fluxes. Col. (7): Probability of exceeding correlation coefficient for fluxes in the null hypothesis. Col. (8): Dispersion of  $\log_{10}(A/B)$  for the detected sources. Col. (9): Total number of sources measured (detections and limits). Col. (10): Partial Kendall  $\tau$ -coefficient describing correlation between luminosities A and B, excluding the effect of distance. Value computed using the formalism of Akritas & Siebert (1996) that extends the Kendall  $\tau$ -coefficient to partial correlation in the presence of censored data (i.e., data including upper limits). Col. (11): Probability of exceeding partial correlation coefficient in the null hypothesis.



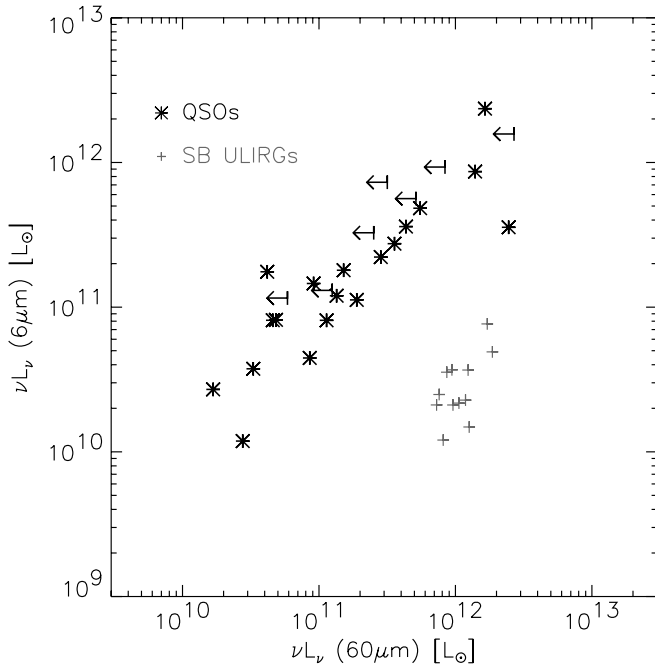


FIG. 7.—Luminosities  $L(6\ \mu\text{m})$  vs.  $L(60\ \mu\text{m})$  for the QSOs and for starburst-dominated ULIRGs. [See the electronic edition of the Journal for a color version of this figure.]

$6\ \mu\text{m}$  continuum or high-excitation lines). Such correlations are not caused by the PG sample selection by  $B$ -band flux and  $U - B$  color, and must indicate a true relation of more luminous QSOs on average being associated with more luminous star formation. In the presence of such a “starburst-AGN connection,” evidence on the causal links connecting the correlated observables has to be obtained from the quality of the correlations, and in particular from comparing the absolute values of the correlated quantities with templates as done above for FIR and PAH.

While the size of the present sample is modest, Table 3 shows that the correlation between PAH  $7.7\ \mu\text{m}$  and FIR luminosities is one of the tighter among the combinations we investigated. Consistent with this trend is the stronger correlation of  $[\text{Ne II}]$   $12.8\ \mu\text{m}$  with FIR than is the case for FIR with either  $[\text{O IV}]$   $25.9\ \mu\text{m}$  or  $[\text{Ne V}]$   $14.3\ \mu\text{m}$ .  $[\text{Ne II}]$   $12.8\ \mu\text{m}$  is a line that is emitted both in the NLR of AGNs (Sturm et al. 2002), with higher excitation lines usually being stronger, and as the strongest MIR line in the spectra of most starbursts (Thornley et al. 2000; Verma et al. 2003). The good correlation of  $[\text{Ne II}]$   $12.8\ \mu\text{m}$  and FIR thus indicates a strong starburst contribution to both  $[\text{Ne II}]$   $12.8\ \mu\text{m}$  and FIR emission, reinforcing the conclusion reached from the starburst-like ratios of these quantities. In a larger sample, these considerations could be expanded to a more rigorous test on the basis of the quality of the correlations. Even in the presence of a starburst-AGN connection, starburst tracers should usually correlate more tightly with other starburst tracers than with AGN tracers. Our sample is not big enough for robust conclusions of this type. Looking at the probability of exceeding the partial correlation coefficients for the full censored data set in the null hypothesis of uncorrelated data (col. [11] of Table 3), it is nevertheless reassuring but certainly tentative that the seven least significant of the 14 correlations discussed are  $60\ \mu\text{m}$  versus  $6\ \mu\text{m}$ ,  $60\ \mu\text{m}$  versus  $[\text{O IV}]$   $25.9\ \mu\text{m}$ ,  $60\ \mu\text{m}$  versus  $[\text{Ne V}]$   $14.3\ \mu\text{m}$ , PAH versus  $6\ \mu\text{m}$ , PAH versus  $[\text{O IV}]$   $25.9\ \mu\text{m}$ , PAH versus  $[\text{Ne V}]$   $14.3\ \mu\text{m}$ , and  $6\ \mu\text{m}$  versus  $[\text{Ne V}]$   $14.3\ \mu\text{m}$ . With the exception of the last, these less significant correlations are all of the type star-

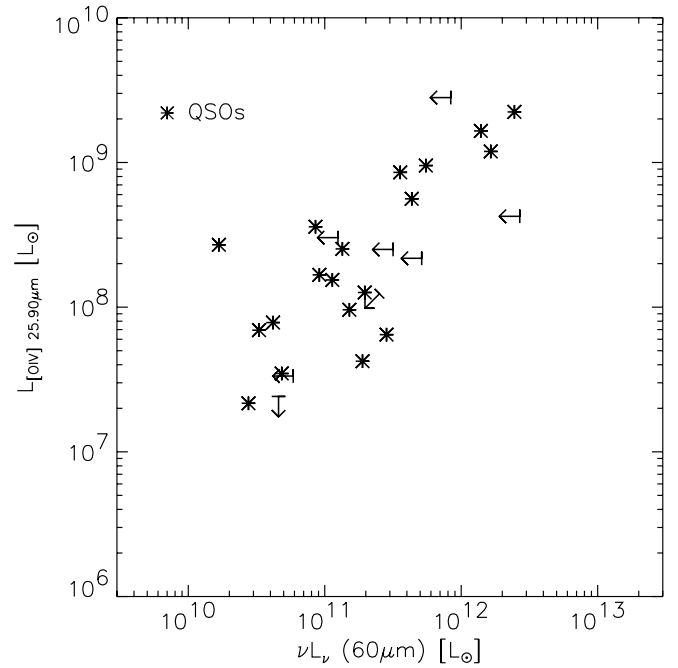


FIG. 8.—Luminosities  $L([\text{O IV}] 25.9\ \mu\text{m})$  vs.  $L(60\ \mu\text{m})$  for the QSOs. [See the electronic edition of the Journal for a color version of this figure.]

burst tracer versus AGN tracer, in the superposition scenario outlined in § 3.2, and provided that the FIR is counted as a star formation tracer.

We conclude that while there are also “indirect” correlations caused by a global correlation of AGNs and starburst luminosity in our PG sample, the relation between PAH,  $[\text{Ne II}]$ , and FIR is real and reflects the starburst component. The most important support for this interpretation is the starburst-like ratios of these three quantities. Starbursts contribute at least  $\sim 30\%$  and likely most of the FIR emission in the average QSO in our sample. An upper limit to the starburst contribution is imposed by the need for a realistic continuation to longer wavelengths of the AGN MIR continuum, which cannot fall off more steeply than the Rayleigh-Jeans-like emission of optically thin dust of an appropriate temperature. The true slope is likely somewhat shallower due to variation in temperature and due to nonnegligible optical depth in part of the MIR-emitting region. We feel that the origin and interplay of silicate emission and continuum in the SED of the AGN is not yet well enough measured or modeled for an accurate AGN continuum extrapolation of this type. This is also due to the need for unambiguous decomposition of starburst, silicate, and AGN continuum. Nevertheless, we consider the minimum pure AGN FIR continuum required by the data to be consistent with our global conclusion from the PAH  $7.7\ \mu\text{m}$  and  $[\text{Ne II}]$   $12.8\ \mu\text{m}$  emission.

#### 4.2. Mid-Infrared Diagnostics and the Starburst-AGN Connection in QSOs

Extending earlier ground-based work (e.g., Roche et al. 1991), Genzel et al. (1998) and Laurent et al. (2000) presented the first empirical versions of the tools now used to separate AGN-powered from starburst-powered infrared galaxies. The basis of these tools is that the intensity of the PAH features in starburst-powered systems traces the starburst’s (FIR) luminosity, while these features are easily destroyed by the strong and hard AGN radiation. Our present study widens the scope of the Genzel

et al. (1998) work by focusing on star formation signatures in high-luminosity bona fide AGNs. We have used our QUEST QSO sample to look for three starburst signatures, strong PAH features, strong [Ne II] lines and strong FIR continuum. Although two of those ([Ne II] and FIR) can also partly originate in AGN environments, we have argued in § 4.1 that the three quantities scale with each other and are tracing significant star formation in most objects of our PG QSOs sample. The measured FIR luminosity  $\nu L_\nu(60 \mu\text{m})$  ranges between  $1.7 \times 10^{10}$  and  $2.5 \times 10^{12} L_\odot$ , covering a wide range of starburst luminosity up to the ULIRG regime, and limits for the remaining QSOs are consistent with starburst emission in the same range of luminosities.

An important result is the correlation of PAH (starburst) luminosity and AGN luminosity in our sample. This extends to higher luminosity a similar result obtained by S02 on the basis of *ISO* spectroscopy of mostly lower luminosity Seyfert galaxies, and of a wide range of optical and near-infrared studies suggesting elevated starburst activity in Seyfert galaxies (e.g., Heckman et al. 1997; Oliva et al. 1999; Gonzalez-Delgado et al. 2001; Imanishi 2003; Kauffmann et al. 2003). Such a connection between small-scale AGN feeding and larger scale starburst activity is plausible (e.g., Norman & Scoville 1988) and may play a role in establishing the black hole mass to bulge velocity dispersion relation in galaxies. Its details are far from trivial, however, and warrant observations with higher spatial resolution to elucidate the spatial structure of star formation in these QSOs (see, for example, Cresci et al. 2004).

Another effect of this connection relates to the interpretation of correlations between QSO properties measured at different wavelengths. Some observed correlations may be indirect, driven by the starburst-AGN connection, as argued for example by Rowan-Robinson (1995) for optical and FIR continua. Haas et al. (2003), however, have used among other arguments the observed correlation between rest frame and FIR continuum in their QSO sample to argue for an AGN origin of the latter. The sensitivity of the *ISO* spectroscopic data they had available did not allow for a conclusive test on the basis of PAH emission. While we confirm the MIR to FIR correlation for QSOs for our PG sample (e.g., Fig. 7), we use our higher sensitivity *Spitzer* PAH  $7.7 \mu\text{m}$  and [Ne II]  $12.8 \mu\text{m}$  data to argue for an indirect nature of this correlation for the luminosity range covered by our sample, induced by a starburst-AGN connection. A similar test remains to be done for the highest luminosity members of the Haas et al. (2003) sample, which are not sufficiently represented in our local PG sample or in the IRS spectra of radio galaxies and radio-loud QSOs of Haas et al. (2005). Such high-quality MIR spectra of highest luminosity QSOs should also be able to test whether a trend for decreasing FIR to MIR ratio at highest optical luminosity (as suggested by Fig. 4 of Haas et al. 2003) reflects an increase in relative AGN intensity compared to the host and its star formation.

A central question in the study of QSOs and ULIRGs is their possible evolutionary relation (e.g., Sanders et al. 1988). Our finding of luminous starburst activity in many QSOs is clearly consistent with such an evolutionary link between ULIRGs (which show ultraluminous star formation and frequent coexisting AGNs) and QSOs (which show ultraluminous AGNs and frequent coexisting starbursts). From such basically energy-related considerations, an evolutionary path with a clear time arrow is, however, difficult to demonstrate and distinguish from more random processes. Including structural and dynamical information, e.g., from other elements of the QUEST program, will better probe this link.

#### 4.3. Direct AGN Heating of Cold Dust and PAHs?

Several models have proposed a direct AGN heating of the FIR emission of QSOs (e.g., Sanders et al. 1989). A basic feature of such models, needed in order to fit QSO SEDs with moderately strong FIR emission, is a significant covering factor by obscuring dust at relatively large (few kpc) distances from the central AGN that is not shadowed by matter closer in. In the model of Sanders et al. (1989), for example, this is accomplished by invoking a dusty galactic disk that is warped into the unshielded AGN radiation on such scales. In such a scenario, the star formation activity and associated PAH emission would be low. The PAH to FIR correlation that we find would have to be due to PAH excitation by the AGN itself at this relatively large distance. The required emission is significant—as we argued above, the ratio of PAH and FIR is similar to that in starburst-dominated systems, and FIR is a significant fraction of the bolometric luminosity for our sample ( $\sim 10\%$  mean for the systems with FIR detections).

A main argument against this scenario is the likely destruction mechanism of PAH by AGN radiation: If this process works through destruction by individual EUV and X-ray photons, then the PAH carriers cannot survive at even kpc distances unless shielded by a large column able to stop the deeply penetrating hard photons (Voit 1992). Such a large absorbing column ( $N_{\text{H}} \gtrsim 10^{22} \text{cm}^{-2}$ ) would, however, prevent the heating of a significant FIR-emitting dust component at large distance, by absorbing the UV “big blue bump” bulk part of the AGN SED. It would also absorb the near-UV ( $< 13.6 \text{ eV}$ ) radiation needed to actually excite infrared feature emission from the shielded PAH molecules. As argued by Voit (1992) and Maloney (1999), PAH molecules can survive even relatively close to a powerful AGN if placed behind large obscuration. Such high obscuring columns could be plausibly identified with the anisotropic obscuring structure postulated by unified AGN models. Exciting these surviving PAH molecules will however require a separate near-UV source, for example by reintroducing a circumnuclear starburst. An indirect transport of AGN near-UV radiation to this shielded material, for example by scattering of UV emerging into the AGN ionization cones, appears unlikely to produce the required large PAH luminosities for  $\sim 1\%$  scattering efficiency, as often assumed on the basis of polarimetric AGN studies (e.g., Pier et al. 1994).

Freudling et al. (2003) and Siebenmorgen et al. (2004a) present observations and models of radio-loud AGNs in which they ascribe the full infrared SED, including sometimes present PAH emission, to the AGN, without invoking additional star formation. Their models (see discussion in Siebenmorgen et al. 2004b) invoke a different treatment of PAH destruction in the AGN radiation field. While this issue certainly deserves future study, their models may underestimate PAH destruction by the AGN. They predict strong PAH emission from optically thin dust illuminated by an AGN at a typical NLR distance, as well as significant PAH emission from an optically thick model for the central region of a nearby AGN that has most of its MIR emission arising in a compact ( $\sim 10 \text{ pc}$ ) region (Figs. 20, 21, and 22 of Siebenmorgen et al. 2004b). In contrast, spatially resolved observations put very strong limits on the PAH emission from such regions of some nearby AGN (Le Floc’h et al. 2001; Siebenmorgen et al. 2004b; Weedman et al. 2005; Mason et al. 2006).

Our interpretation is also consistent with other, partly circumstantial, evidence for star formation in QSOs. Canalizo & Stockton (2001) find optical spectroscopic evidence for relatively recent  $\lesssim 300 \text{ Myr}$  star formation in a sample that ranges from ULIRGs to some of the moderately FIR-bright PG QSOs of our sample.

Veilleux et al. (2006) find some PG QSOs brighter than the  $H$ -band fundamental plane, possibly indicating circumnuclear star formation. Molecular gas detections of PG QSOs (e.g., Evans et al. 2001; Scoville et al. 2003), while not directly probing star formation, suggest sufficient material to power the FIRfar-infrared emission if star formation is efficient.

#### 4.4. Comparison to QSO Star Formation Estimates based on [O II] $\lambda 3727$

Our finding that star formation activity is able to power the FIR emission is in contrast to the result of Ho (2005). For a PG-based sample partly overlapping with our sample, he found insufficient star formation from an analysis using the [O II]  $\lambda 3727$  line as a star formation tracer. Large and uncertain corrections for extinction of this tracer are likely the main contributor to this discrepancy.

Ho (2005) used [O II]  $\lambda 3727$  fluxes for his QSOs from the literature and the calibration of Kewley et al. (2004) for *extinction-corrected* [O II]  $\lambda 3727$  as a star formation indicator that is also a function of metallicity:  $\text{SFR}([\text{O II}], Z)$ . Kewley et al. (2004) base their work on a sample of nearby field galaxies with detailed integrated optical spectroscopy, and star formation rates spanning 4 orders of magnitude centered on  $\sim 1 M_{\odot} \text{ yr}^{-1}$ . They demonstrate that [O II]  $\lambda 3727$  is a star formation indicator as good as  $H\alpha$  over this range, provided extinction can be corrected for individual objects, and individual metallicities are known.

To apply this calibration to QSOs whose optical spectra are strongly dominated by AGN emission, Ho (2005) made three assumptions: (1) screen attenuation of  $A_V = 1$  toward the star-forming regions, (2) metallicity twice solar, (3) one-third of the [O II]  $\lambda 3727$  emission comes from star formation. Another implicit assumption is (4) aperture corrections to [O II]  $\lambda 3727$  can be ignored for the hosts of this QSO sample with median  $z \sim 0.09$  observed with  $2''$ – $5''$  optical spectroscopic apertures. Under these assumptions, Ho (2005) infers star formation rates of at most  $20 M_{\odot} \text{ yr}^{-1}$  but often much less, and typically an order of magnitude below those inferred by ascribing the FIR emission to star formation.

While all four assumptions contribute to the uncertainties of this approach, we believe that assumption 1 about the reddening to the star-forming regions is the key to the systematic difference to our *Spitzer* results. As noted, e.g., by Kewley et al. (2004), extinction is a strong function of intrinsic [O II]  $\lambda 3727$  luminosity. At the short wavelength of [O II]  $\lambda 3727$  where  $A_{\lambda} \sim 1.5 \times A_V$ , increased dust extinction can relatively easily offset much of an increase in intrinsic line luminosity. Since the FIR luminosities of our quasars reach beyond  $10^{11} L_{\odot}$ , it is instructive to compare to the systematic optical spectroscopic study of a complete sample of luminous infrared galaxies by Poggianti & Wu (2000), which is addressing objects with  $L_{\text{FIR}} \sim 10^{11.5} L_{\odot}$  for our cosmology. More than half of their objects have so-called e(a) optical spectra, characterized by absorption in the higher Balmer lines, weak [O II]  $\lambda 3727$ , and significant obscuration of the emission lines.  $E(B - V)$  is  $\sim 1.11$  even in the simplifying screen assumption, which still ignores regions in such highly dusty objects that are too obscured to contribute to the optical lines. With observed  $L(H\alpha) \sim 10^{41} \text{ ergs s}^{-1}$  and  $[\text{O II}] \lambda 3727/H\alpha \sim 0.23$ , they are in the regime of or below the portion ( $\frac{1}{3}$ ) of the QSO [O II]  $\lambda 3727$  luminosities that Ho (2005) ascribes to star formation, already considering that [O II]  $\lambda 3727$  aperture corrections may be more significant for the Poggianti & Wu (2000) sample which has median  $z = 0.0324$  and similar spectroscopic apertures. Similar arguments apply, to a lesser degree, to the Poggianti & Wu (2000) objects with spectral classifications other than e(a).

There is a large population of dusty luminous starbursts that could fit the weak [O II]  $\lambda 3727$  emission of the Ho (2005) QSOs.

In summary, while the QSO optical data are consistent with the low star-formation rate interpretation of Ho (2005), they are also consistent with much higher star formation rates. This is because the optical analysis of Ho (2005) is based on a single line that is strongly extinction sensitive, and no extinction constraints are available for this component from the optical data. Less extinction sensitive data like the *Spitzer* infrared spectra are needed to break this degeneracy, and suggest more substantial star formation rates. Some of the QSO host optical spectra may share properties of infrared galaxies with e(a) optical spectra: little obscuration toward the stellar continuum spectra dominated by an older postburst component, but still significant obscuration of the active star-forming regions (Poggianti & Wu 2000).

#### 4.5. Implications for High-Redshift QSOs

Deep submillimeter and millimeter photometry has led to the detection of rest-frame submillimeter and FIR dust emission from radio-quiet QSOs at redshifts up to 6.42 (e.g., Omont et al. 2001; Isaak et al. 2002; Bertoldi et al. 2003). It has been variously argued through indirect arguments like CO content that this emission is star-formation-powered (e.g., Walter et al. 2003), implying that these QSOs coexist with extremely powerful  $\gtrsim 10^{13} L_{\odot}$  starbursts. Our results support a starburst origin of QSO FIR emission, but do not extend to this luminosity and redshift regime. If the ratio of PAH to FIR emission for these QSOs is similar to the one in the local QSOs and in ULIRGs, detection of PAH emission on top of a strong continuum may be within reach of *Spitzer* spectroscopy. PAH emission from similar luminosity SMGs is detectable at ULIRG-like ratios to the FIR emission (Lutz et al. 2005). Luminous PAH emission has also been reported in MIR selected samples of  $z \sim 2$  infrared galaxies (Yan et al. 2005). Probing for PAH emission may currently be the only way to verify the assumption of simultaneous strong star formation and QSO activity in high-redshift QSOs.

### 5. CONCLUSIONS

Sensitive *Spitzer* MIR spectroscopy reveals the widespread presence of “PAH” emission features in  $z \lesssim 0.3$  QSOs from the Palomar-Green sample, indicating the presence of powerful  $[\nu L_{\nu}(60 \mu\text{m}) \sim 1.7 \times 10^{10} \text{ to } 2.5 \times 10^{12} L_{\odot}]$  star formation activity in these systems. Starburst and AGN activity are connected in QSOs up to these high luminosities. By comparing the ratios of PAH  $7.7 \mu\text{m}$ , [Ne II]  $12.8 \mu\text{m}$ , and FIR emission in QSOs with starbursts we conclude that for the average QSO in our sample at least 30% and likely most of the QSO FIR emission is due to star formation. The data suggest a trend with the star formation contribution being the largest in the most FIR-luminous QSOs.

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